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TO: Director
Office of Advanced Research and Technology
National Aeronautics and Space Administration
Washington 25, D.C.

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SUBJECT: Progress Report for the Period 1 April 1963 -
30 September 1963. NSG 107-61 "Functional Extension of the
Human Hands."

Progress is reported for this period in the following categories:

Completed Work

1. Characterizing nonlinear adaptation of the human operator by the Weiner-Lee theory.
2. Pursuit sampled-data tracking model.
3. Simple adaptive controller with transmission delay in the adaptive loop.
4. Remote touch display, phase one.

Continuing and New Work

5. Effects of transmission delay on human manipulative control.
6. Experiments with modified hot lab manipulator.
7. Calibrating discrete arm movements to visual displacements.
8. Precognitive and manipulative control model developments.

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1. Characterizing Nonlinear Adaptation of the Human Operator by the Wiener-Lee Theory.¹

This study applies the statistical theory of nonlinear control systems developed by N. Wiener and Y. W. Lee to characterize the human operator in a simple tracking loop.

Two experiments were performed. The first examined the inherent nonlinearities of the closed-loop human operated system. Results indicate that low order nonlinearities do not account for any substantial portion of the linear remnant, confirming a hypothesis derived from investigators who have used linear techniques.

The second experiment examined the ability of the operator to adapt to a nonlinear process. The operator was placed in a loop with a nonlinear process. But with the given inputs minimum mean-squared-error would be achieved by a linear system. Thus, assuming the operator adapted a mean-square-error criterion, his best strategy was to adopt the inverse of the nonlinear process. Results showed some tendency to compensate for the nonlinearity; but results were not sufficiently definitive to infer the degree of "inverseness" of the operator's characteristics.

A discussion of the theory, measurement technique, and form of results of this initial application of the general Wiener-Lee theory to the human operator is included in the reference.

2. Pursuit Sample-Data Tracking Model.²

A sampled-data pursuit tracking model was formulated, based upon hypothesized operations the human operator performs in pursuit tracking additional to those of compensatory tracking. Thus the model was conceived as an extension of the type model formulated by Bekey and by Westcott and Lemay for the compensatory tracking problem. It included a proportional-plus-derivative element operating directly on the input as well as an error sensitive term, both of which operated through a "muscle" producing constant duration ramp excursions with velocities proportional to pulse (sampled) inputs. The sampling rate was 5 per second.

The frequency characteristics of the model were evaluated on a GE 225 digital computer where the model itself was actually constructed from electronic analog and relay components. Good agreement

between the models' and the humans' (using Elkind's data) frequency characteristics was found.

The time response was also evaluated. It was found that on occasions when the stimulus waveform looks as though (considering its acceleration) it will reverse direction, but does not, both the human controller and the sampled data model show definite reversals before they correct themselves and follow the input. The continuous linear model will not behave this way.

3. Simple Adaptive Controller With Transmission Delay in the Adaptive Loop.³

An analog computer model of an adaptive control system was set up to study the effects of a transport delay in the adaptive loop. This simulated, for example, a control system operating a distance from earth with local feedback for non-adaptive automatic control but a long distance loop back to earth for adaptation and learning.

The closed-loop system, excited by a square wave, had to adapt to secular changes in a damping parameter. Forward loop gain was adjusted by a simple adaptive mechanism of increasing gain system if error decreased, and vice versa.

The controller gain value was found to respond in a limit cycle. The minimum stable limit cycle time was found to be directly proportional to the adaptive loop delay.

Analog experiments showed that performance is affected by the ratio of parameter variation rate to signal variation rate. When this ratio is sufficiently small, an interaction causes "noise" in the adaptive loop at the input signal frequency. The effect of such noise may be attenuated by a low-pass filter in the adaptive loop, but only at the expense of the effects of an additional adaptive loop delay. A trading relation between unattenuated noise and filter delay was determined empirically.

4. Remote Touch Display.⁴

Experiments have been completed on the first phase of development of the remote touch transducer. As detailed in the previous progress report, the sensing element consists of a plyable stress optical material (epoxy in this case) with a light reflective coat on one side and a circular

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polarizer on the other. Light incident from the polarizer returns from the reflective coat and passes back through the polarizer in such a way as to cause a high density of color bands as a function of stress (strain) gradient. Color is a function of the third spatial derivative of deflection or the first derivative of curvature. Color gradient is a function of the fourth derivative of deflection, the second derivative of curvature, or is directly proportional to loading.

An experiment was performed to see what difficulties subjects had in distinguishing everyday objects from one another in terms of their pressure pattern. Three "matched" groups of objects were presented: (1) directly to the skin on the flat palm, (2) to the eyes using the stress-optical laminate, and (3) to the eyes using the stress optical laminate but with the polarizer removed. The latter had the effect of eliminating the color spectral fringes, leaving only a less sensitive light intensity gradient with curvature of the "skin" where the "touched" object deformed it. Subjects in the experiment were permitted to move their real or stress optical "skin" freely relative to the objects being identified. Results showed that identification times of (b) averaged 1.5 those for (a), while times for (c) averaged twice those for (a). Errors of identification were considerably less with both visual touch sensors than with the actual skin. Why this was so is not clear. It should be remembered that subjects were not seeing the objects per se, they were seeing only the patterns of pressure between the objects and the artificial "skin".

5. Effects of Transmission Delay on Human Manipulatory Control. ^{5,6}

The work completed up to the time covered by this report consists essentially of:

- A. Developing the "minimal manipulator" into a usable form and providing for a delay in the operation of its three degrees of freedom.
- B. Demonstrating that the presence of delay does not result in "unstable" operator behavior for manipulation tasks. This is due to the operator's adopting a strategy of waiting to get accurate feedback after a move.

- C. The proposal of a simple method of predicting task completion time with delay from measures of operator-manipulator performance obtained when there is no delay.

Present Efforts Consist in:

- A. Attempts to replicate the original experiment on transmission delay. Experiments are reported in full in Ref. 5. The results are somewhat inconclusive, and it is inferred that there is a considerable learning effect confounded with the delay-time variable. There appears to be no reason for abandoning the proposed scheme for predicting task completion time, however.
- B. One of the measures used in the prediction scheme, N, the number of times feedback is needed to complete the task, is examined from several viewpoints.
- i. A Monte Carlo method is proposed for trying to predict from data in the literature the average number of open-loop moves to achieve a given tolerance--a number closely related to N.
 - ii. The effects on N of properties of the manipulator are discussed and experimental work is proposed.
 - iii. It has been found, when certain tasks requiring visual feedback are performed with only periodic brief flashes of light for illumination, that the relation between the number of flashes needed and the flash rate appears to be linear and have as constants the two measures used in the prediction scheme. Controlled experiments are reported in confirmation, and some possible causes for the effect are examined. No firm conclusions can, as yet, be drawn. It is apparent, however, that periodic stroboscopic illumination may provide a means of measuring the relative sensitivity of a task to delay when performed with a given manipulator-operator combination.

6. Experiments With Modified Hot Lab Manipulator

A conventional remote handling device of the nuclear hot-lab type which had been instrumented with electric motors on the various degrees of freedom and used by H. Ernst in a previous M.I.T. thesis. This has been modified so that the motors may be switched on and off under human control. The switches are incorporated in a small hand held device having degrees of freedom spatially analogous to those of the manipulator. Thus there is a compatibility between manual responses to activate or de-activate switches and the resulting actions of the artificial hand. The hand has also been instrumented with electrical contact sensors (it had previously been shown on a simpler manipulator that control was feasible with no visual feedback) and only this elementary form of contact sense displayed to the human operator. Experiments with this device are proceeding.

7. Calibrating Discrete Arm Movements to Visual Displacements.

Experiments are planned to study how the human operator calibrates his kinesthetic displacement sense against his visual sense in making discrete open-loop movements in response to oscilloscope spot displacements. It is found that simple teledeltos chart recorder paper makes an ideal device to provide electrical resistance proportional to displacement of a freely moved hand held stylus.

8. Precognitive and Manipulative Control Model Developments.⁷

Plans are being made for a digital computer simulation of one or two finger manipulation of simple objects on a plane. Inertial, elastic and friction forces between fingers and objects will be represented. Visual and touch sensing will activate control logic which in turn will drive the finger(s) to move so as to modify positions of objects until some criterion is satisfied.

9. References

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